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No Fault Found Events in Maintenance Engineering Part 1: Current Trends, Implications and Organizational Practices

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Abstract

This paper reviews the literature dealing with the nature and characteristics of no-fault found events within maintenance lines. Increasing systems complexities have seen a rise in the number of unknown faults that are being reported during operational service. Units tagged as 'No-Fault Found' are evidence that a serviceable component was removed, and attempts to troubleshoot the root cause have been unsuccessful. This scenario worsens when faults occurring at the component level are intermittent in nature. Here, the paper describes the prominent issues that have persisted across a variety of industrial applications and processes for decades. Some recent developments including standards, financial implications and safety concerns are highlighted.

Keywords:
No fault found; maintenance procedures; human factors; safety; cost

1. Introduction

The work presented in these two-part series of papers is an attempt to review the recent developments on addressing the root causes of No-Fault Found (NFF) events, ranging from simple faults in electronics, to the way in which an organizational structure is setup. The novelty relies on presenting an interpretative survey of NFF issues, relevant standards, organizational procedures, economic efforts, technological solutions, diagnostic challenges and recommendations on testability for managing NFF.

Reliability analysis requires the synergy between a systematic approach that has clear definitions of the reliability parameters, and a comprehensive collection of analysis techniques and procedures. The reducing size of electronics and their complex interactions have forced designers to improve their understanding of failures from a multidisciplinary perspective. This becomes significantly important when considering a class of system faults that cannot be easily located, diagnosed or even reproduced under standard maintenance testing regimes [1, 2, 3]. The existence of the 'No-Fault Found' phenomenon has had a definitive negative impact upon critical system stakeholder requirements, which at the top level, often includes systems safety, dependability and life-cycle costs. It is therefore essential to prevent NFF events or (at the very least) reduce the impact it has on the business operation. To deliver stakeholder requirements efficiently, certain aspects (such as suitable knowledge and technical competence) must be promoted, enabling domain experts to acquire (and retain) additional skills for long-term professional activities [4]. Issues on safety performance and cost cannot be compromised, and hence it is essential to discuss topics on information quality (when data is presented to the operators), response times (on early symptoms of failure) and knowledge ambiguity (on operation and maintenance of equipment) of the test procedures and practices in place. These arguments place an emphasis on the requirement to prepare maintenance experts with specialized intelligent systems, which can detect early anomalies and capture adequate information for investigation.

Both papers provide an industrial outlook to the problem, Part 1 in particular covers the following key areas:

1. Research Methodology
2. The Problem Statement
3. Understanding the Taxonomy
4. Standards in NFF
5. Organizational Procedures and Adminstration
6. Financial Imperatives
7. Safety Implications

The remainder of the paper is structured as follows: Section 2 describes the methodology adopted to conduct this review. Recent trends and targeted journals has been highlighted. Section 3 presents the literature associated with NFF events, economical impact on the business and customers. Sections 4 and 5 provide discussions on NFF taxonomy and organizational/cultural aspects, respectively, followed by sections on financial implications and safety considerations. In the end, some conclusions are reached from the preceding theoretical analysis.

2. Research Methodology

One of the goals of this study is to understand the state of current NFF research. This is accomplished by investigating the

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existing published material to yield insights for industrial practitioners and academic researchers on the major trends, significant works, and future directions. Therefore, the authors have compiled a systematic reference point for burgeoning NFF literature. As research within this area is of practical importance, the scope of this investigation covers the time frame between 1990-2013, whilst concentrating on the last decade in particular (as this period has been deemed to be have contributed the most papers on the topic). To accomplish the study aims, this research is based reviewing a variety of journals and conference articles, all of which are directly related to NFF concepts and its application. Due to the scope and diversity, articles were found to be scattered across a range of sources, and thus a literature search was conducted using the following electronic databases:

1. Scopus
2. Emerald insight
3. Science Direct
4. IEEE Xplorer
5. IET Digital Library

One of the main challenges as part of this review was the lack of a unique/exclusive term that can signify NFF events, since a true gauge of the problem is difficult to investigate. Therefore, the literature search was based on the following descriptors:

1. No Fault Found (NFF)
2. Cannot Duplicate (CND)
3. Fault Not Found (FNF)
4. No Trouble Found (NTF)
5. No Defect Found (NDF)
6. Hidden Failures
7. False failures

All of these listed terms have actually been used by organizations to describe similar events (with some subtle differences). None-the-less, this article assembles all of the above descriptors under the NFF umbrella, and makes a recommendation for establishing a formal NFF taxonomy.

Before continuing any further, the authors would like to discuss the limitations associated with this review:

1. A limited descriptors are used (as listed earlier)
2. The findings are based on information that was collected from academic journals, conferences and discussions with maintenance personnel
3. A limited number of papers were used (only the articles in the selected databases have been included)
4. The time period is limited between 1990-2013

The authors believe this review to be a comprehensive one, and can be used for gaining an understanding of NFF knowledge. Also, despite the fact that the selected time period spans over the last two decades; the last ten years are believed to be the most productive from a research point-of-view, and hence will be able to enrich the contents of these papers.

Following the database searches, articles were then reviewed in order to eliminate the ones which were not related to NFF. In total, the authors were able to identify 154 published papers for the period 1986-2013; this includes 38 published journals, 84 conference papers and an additional 32 journal publications (which were cited by the papers). Although these two papers present conclusions primarily based on the identified 38 journals, the other 116 papers (32 journals and 84 conference papers) have been used to assist with underlying discussions through out the review process. Furthermore, each retrieved article was carefully reviewed prior to making a judgment with regards to its inclusion in this survey.

Table 1: Breakdown of targeted journals for the 38 NFF publications

Journal	No of articles
Microelectronics Reliability	7
Quality in Maintenance Engineering	5
Reliability Engineering & System Safety	3
Journal of Aerospace Engineering	2
IEEE Design & Test of Computers	2
IEEE Transactions on Reliability	2
SAE Technical paper	2
Test Engineering and Management	2
Quality and Reliability Engineering International	2
IEEE Transactions on Components and Packaging Technologies	1
CIRP Annals-Manufacturing Technology	1
IEEE Transactions on Dielectrics and Electrical Insulation	1
Journal of Productivity and Quality Management	1
IEEE Transactions on Device and Materials Reliability	1
Research in Engineering Design	1
Aircraft Engineering and Aerospace Technology	1
International Journal of COMADEM	1
Electronic Product Design	1
IEEE Transactions on Electronics Packaging Manufacturing	1
Journal of Design Research	1

Table 1 lists the journals that have been targeted for publication of NFF research; where all 20 journals are related to system reliability and maintenance. This is an interesting result as one of the major current issues with NFF are the cost implications[1], but there are no business oriented or cost related publications that can highlight its importance. In any case, despite the fact that the authors believe that journals should be the primary resource that must be used to acquire and disseminate knowledge; due to the scale of the subject area, some conference papers, news reports, and unpublished working papers were included to help with the underlying discussion/context.

[1]This is discussed in Section 7 on Page 10.

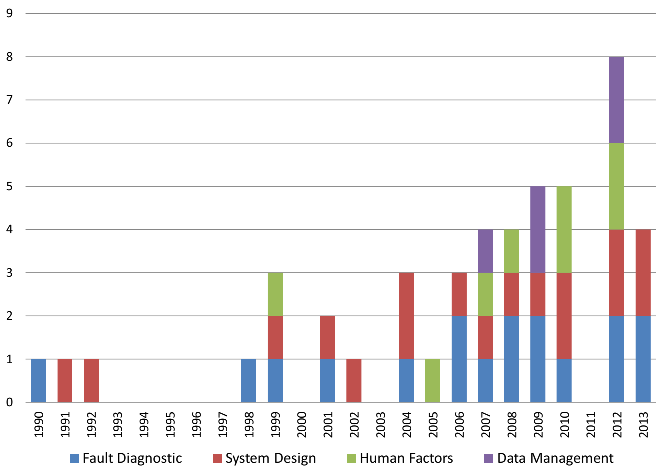

Figure 1: Classification of NFF journal publications since 1990

2.1. *Classification of the reviewed literature*

The authors have grouped each of the 38 journal articles under specific categories, which involved several discussions amongst all four authors until a mutual agreement was reached as to where an article should be classified. The structure includes a content-oriented categorization of the NFF literature into four main areas. These themes were identified, through an interactive dialog with senior industrial delegates, as being the most influential contributors to the NFF problem [5]:

1. Fault diagnostics - this includes publications that discuss aspects of NFF comprising of sensors, troubleshooting, fault isolation manual, calibration of built-in-tests and environmental effects
2. System design - this includes publications that discuss operational feedback, Key performance indicators or benchmarking and cost implications.
3. Human factors - this includes publications that discuss supply chain, communication, training/education, correct use of equipment, warranty claims and accountability
4. Data management - this includes publications that discuss data trending, e-logs, data fusion/mining

Table 2 lists the 38 articles, and how they have been classified. This will be a very useful resource for researchers searching for journals within a specific area. Fig. 1 demonstrates the increasing interest in the area from a maintenance engineering perspective[2], where fault diagnostics and system design appear to be the main focus through out the listed years. These are probably due to increasing system complexities and cost implications on maintenance programmes. Also, this is possibly due to the downgrading of the world economy since 2008, forcing e.g. civil airliners having to reduce costs, whilst increasing the availability of their aircraft. In the military domain government spending cuts, particularly within the UK, have significantly downsized the workforce available for maintenance activities, and hence has had a knock on effect on maintenance regimes.

[2] A similar trend was observed from the number of conference papers that have been presented in the last five years, where the leading three conferences that published NFF papers include: Annual Reliability and Maintainability Symposium, IEEE Aerospace Conference and IEEE AUTOTESTCON.

Table 2: Classification of NFF literature

Category	References
Fault diagnostics	[1, 2, 3, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19]
System design	[1, 13, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32]
Human factors	[1, 20, 32, 33, 34, 35, 36, 37]
Data management	[1, 20, 37, 38, 39]

[1] [1, 26] are review papers on the NFF.

3. The Problem Statement

A typical maintenance process within an organization can be observed in Fig. 2. Here, it is important to understand the concept of how NFF instances can manifest themselves at various levels. When an operator records a system error, maintenance personnel are notified, who will attempt to investigate the reason for the system malfunction. If no causes are discovered, the failure will be tagged as ‘No Fault Found’. There may be various reasons that contribute to this overall process. Perhaps the operator (or maintainer) lacks of knowledge of the system, or has received insufficient support to carry out the fault diagnosis. There can be many reasons including having minimal understanding of the manuals, lack of equipment or operational pressures. Such occurrences have predominantly been associated with electronic equipment [1, 32, 24, 13].

The aerospace industry has reported the majority share of electronic NFF faults, primarily within aircraft avionics. Although, some studies suggest that NFF events generally occur after an initial warning alarm has been triggered, indicating a system fault [1, 7]. This alarm, which does not provide any other direct diagnostic information, triggers maintenance activities that ‘repair’ the faulty unit as it is removed for testing. During the testing phase, the situation arises where the same symptoms cannot be detected (or reproduced) with the standardized test equipment and procedures, or the exact nature (or location) of the fault is unable to be determined; as a result the unit is labeled NFF. This can be regarded as a ‘diagnostic failure’ (or Fault Not Found) and the actions or procedures which are then taken by the organization responsible for the maintenance activity are of paramount importance to ensure safety and reduced costs.

In this paper, the common causes of NFF events are categorized into the following set of classes: technical, organizational, procedural and behavioral. Technical causes involve things such as undefined or limited performance measures, inadequate information on operating environment, designs unsuitable for robust testing or a lack of robust fault models. Organizational

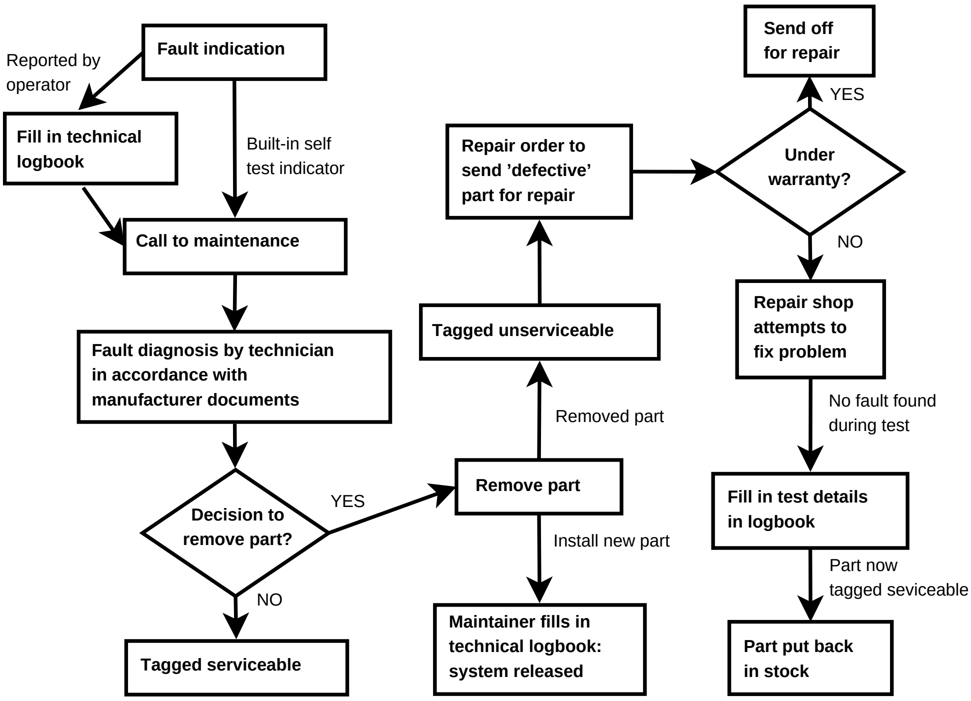

Figure 2: The simplified repair process during a maintenance action.

and procedural issues are driven by the business and commercial environment and encompass a lack of training and training tools, time pressures on maintenance operations, organizational cultures with no cross-functionality; in addition a lack of commitment, sharing information and knowledge between designers, manufacturers, service providers and operators are also organizational issues. Behavioral causes, commonly also referred to as 'human factors', arise directly from the maintenance personnel themselves, and are created by staff creating discrepancies in test procedures, reporting faults incorrectly or incoherently, applying the wrong processes coupled with a lack of communication between maintenance personnel and other experts.

Khan et al. (2012) [40] have attempted to address the scale of the problem as a sequence of events. The sequence begins during operational service when a Built-In-Test (BIT) fails (or the operator reports the possibility of an error), and independent functionality tests are then triggered to verify the fault/failure. If it cannot be repeated, a failure to diagnose the problem is recorded. If the functionality tests fail, then further off-line tests within the maintenance shop/depth are used to diagnose the system fault to a group of Shop Replaceable Units (SRUs) that are suspected of being the source of the Line Replaceable Unit (LRU) failure. Depending upon the accuracy of the diagnosis at this level, ideally only one SRU is called out; less precise diagnostics might call out two, three or more SRUs. The components are then sent back to the depot/workshop for functional testing using Automatic Test Equipment (ATE), where it will be concluded if the component was healthy or falsely replaced, or it is definitely faulty and the diagnostic testing is inadequate [41].

James et al. (2003) [42] investigated various NFF situations while focusing on developing practical guidance for designers and project managers to facilitate better understanding of the unknown failures and procedural improvements. The research summarized a comprehensive breakdown of the potential reasons for NFF events:

1. Operator Policies (e.g. short turn round times, availability of spares, aircrew mission priorities)
2. Failure in recording/reporting (e.g. quality of aircrew debrief, poor data coding)
3. Maintenance practice (e.g. lack of maintainers training, technical publications inaccuracy)
4. Repeat removals (e.g. little use of maintenance history, 'rogue units')
5. Workshop ineffectiveness (e.g. pressure to produce throughput, lack of staff training)
6. Inadequate test coverage (e.g. test philosophy across maintenance levels, comprehensiveness of test)
7. Interpretation of results (e.g. fault code interpretation, training of workshop staff)
8. Intermittent system connection (e.g. connector integrity, harness/loom integrity)
9. Product contains intermittent faults (e.g. solder joints, PCB weakness)
10. Incompatible system design (e.g. BITE coverage, software tolerances)

It is clear that a great many of the diagnostic failure events which are of interest occur in electrical and electro-mechanical systems, but research shows that mechanical systems also give rise to similar difficulties, but are far less published. The causes of failures in these systems are similar to those in electrical systems, such as ageing, poor maintenance, incorrect installation or usage; however, it seems that it is much easier to predict the effects upon the systems operation with mechanical failures. As a result this allows an inspection criteria to be developed during the design phases. It should be noted that as with many electrical failures, mechanical failures can be intermittent in nature and only occur under specific operating conditions [40].

In electronic systems, loose connections probably cover most of the fault cases that have been published as NFF [13, 43]. Some of the more common and well known include poor solder joints, faulty electrical components, damaged PCBs and problems with internal wiring. In addition, electronic failures are not considered as static (or random) events, but a process of mechanical and material changes. These changes will not always lead to a loss of operation for the system, even though their components are out of specification. This is because electronics have an inherent self-compensating aspect which makes the task of diagnostics difficult. In addition to this self-compensation, degradation of failure modes will manifest differently depending upon the operating environment and may offset one another depending on circuit configuration [43].

3.1. Business Impact

Customers often fall under two categories: those that maintain their own fleet (e.g. aircraft, vehicles, ships, etc) without assistance, and those who sub-contract their fleet maintenance completely (or partly) to a maintenance contractor. NFF events impose a maintenance burden on both of these, the former for the customer, and the latter for the maintenance contractor. When the failure occurs, there is an increase on the fault arising rate[3], leading to financial implications on maintenance (due to repeated investigation and equipment exchange) and the supply chain costs (due to potentially serviceable equipment being returned for repair). There will also be a reduction in the overall availability of the fleet, depending on the reliability, maintainability and logistical factors, all of which contribute to the cost of resolving an unknown fault.

The costs involved with NFF issues can often be quantified by measuring the proportion of the repair budget that is spent or 'wasted' on the maintenance activities involved in locating the root cause of the failure. Most avionics engineers agree that the estimated NFF rates for any given system or equipment is between 30%-50% [1, 44]. Consider the theoretical scenario: An avionics equipment, fitted to a fleet of aircraft fails every 300 hours. The fleet flies 30,000 hours per year, and the cost to return one equipment through the supply chain for repair is approximated to be £10,000. With the worst-case NFF rate at 50%:

Fault rate: $\frac{30{,}000}{300}$ = 100 returns per year
NFF occurrence: 50% of 100 = 50
50 NFF returns cost 50 x £10,000 = £500,000 per year

The numbers above are estimates for just one complex equipment. Combat aircraft have many other items that cause significant annual expenditure on NFF. In addition, there are hidden costs of 'at aircraft' diagnosis and recovery including spare-parts, maintenance man-hours, aircraft down-time, etc., which indicates that the NFF burden for a typical fleet becomes £Millions per annum.

4. Understanding the Taxonomy

Moffat (2008) [12] advocates that taxonomies of the electrical, mechanical, chemical and thermal stresses are a contributing factor to the various stages of ageing and/or failure. If this argument is extended, it becomes necessary to understand what exactly is meant by 'an NFF failure'. It should be emphasized that the authors have not yet identified any singular agreement about its term, use and application within common industry organizations, let alone commonality in meaning across industry sectors. This is exacerbated by the sheer number of terms and disparities in the taxonomy, which is used to describe the failure event itself, particularly in different countries. Within the UK (and most of Europe), the acronym 'NFF' has generally been adopted. In the USA, terms such as ReTest OK (RTOK), Cannot Duplicate (CND), Trouble-Not-Isolated (TNI), Fault Not Indicated (FNI) and No Trouble Found (NTF) are but a few of the more common variants. However, fundamentally they are all evidently applied to the same event, which requires exploration to try and arrive at a clear and concise solution to a reported problem. The proliferation of terms certainly suggest the need for a definition of the NFF phenomenon.

A set of NFF guidelines were introduced within the ARINC 672 report [45], presenting an generic procedure that can help understand the fundamental principles, relationships, mechanisms and interactions connected to NFF failure situations. The ARINC 672 also presented an NFF definition for the airline industry, defined as: *"Removals of equipment from service for reasons that cannot be verified by the maintenance process (shop or elsewhere)"*. But the problem is really even boarder than this as the statement should also cover cases when no fault is found at the aircraft (or equipment), due to which it is returned to service with nothing found. Also, many faults that are classified as NFF do not result in equipment removal from the aircraft[4]. So perhaps NFF should be described more as a maintenance failure: *Any reported fault which results in nugatory maintenance and logistical effort* [20]. To achieve high rates of diagnostic success is surely what is expected from any maintenance activity. This implies identification of a root cause, if there is one, or positive identification that there is no root cause if otherwise. Only in that case will the correct and most appropriate maintenance activity be carried out, allowing removed units' integrity to be ensured and hence able to be safely returned to service.

What becomes clear, whilst reviewing the associated literature and discussions with various industrial organizations

[3]NFF is generally regarded as a fault for statistical purposes, although, some industries may use discrete fault codes

[4]many varied factors can cause this e.g. operator policy, operational expediency, etc

Table 3: Results from a Recent survey showing a disparity in terminology.

Term	Use (%)
No Fault Found	56
Unable to Reproduce Fault	18
Cannot Duplicate	14
No Trouble Found	4
Repeat Arising	2
Re-test OK	2
Fault Not Found	2
No Evidence of Failure	1
A-799	1

within the UK, is that there are no approved code of practices in place to ensure correct identification, reporting and mitigation of these problems. It seems that the disparity between terminology and definitions may have affected the ability to deal with the NFF issue, despite the earliest call for standardization of taxonomy for NFF being in Simpson et al. [46]. Therefore, a notable driver that contributes to the problem is the lack of standardization, clarity and inappropriate usage of taxonomies. Table 3 shows the results of a recent survey conducted by Copernicus Technology Ltd into the causes and perceptions of NFF in the aerospace industry, responded to by approximately 120 aerospace organizations [47]. The results show that approximately half of the respondents refer to it as 'No-Fault Found', but the other half refers to it in a variety of other terms.

To introduce a change, there is a definite need for establishing policies, procedures and in some cases an overhaul of the terminology used for NFF events [48]. UK aerospace engineers have expressed their belief that the term 'No-Fault Found' quite possibly provides a hindrance in reducing NFF events. The start of this may be to describe the issue as a 'Fault Not Found' [40, 42], which has a more positive behavioral sense, rather than NFF, which suggests an attitude of resignation, that there was probably no fault there anyway. In order to culturally shift the workforce to change from the general reactive mentality on to a much more proactive approach, FNF implies that more work has to be done to solve the problem. It may also be the case that NFF requires branches of sub-terms to describe the event from the perspective of different levels. In any case, in order to be objective, it must be recognisee that not all industry sectors will agree with this aerospace stance. A leading international construction vehicle manufacturer disagrees with the need for this and has claimed that changing and adopting a universal name will not change anything. The problem is still the same [40]: *"We used the term 'Trouble Not Identified' for a while years ago. We got that term from automotive. It just confused people. The culture of acceptance is driven from a lack of understanding of the real drivers of NFF"*.

What is interesting about this statement is the idea that there is a lack of understanding on *'... the real drivers of NFF'*. This supports what is being seen in the literature with over simplified descriptive terms, attempts to classify the root cause as NFF rather than recognizing it as an element in a chain of events which are influenced by organizational behavior and culture as well as processes and procedures. These are the drivers which need to be understood and it is believed by the authors that standardizing taxonomy, unifying definitions, championing the correct terminology and creating a high level of coherency are essential to push forward the understanding of these driving factors.

5. Standards for NFF

Standards can be used to guide industries to effectively promote efficient operation and improve reliability. Specific best practices can be tailored to different application areas; and are currently used for maintenance support that advocate developing policies to meet process objectives. Specific standards have been introduced over the years to improve system maintenance, and to reduce overall scheduling costs, e.g. the Reliability Centered Maintenance standards (RCM) i.e. IEC 60300-3-11 [49] and SAE JA1012 [50], present guidelines for developing and regulating an initial maintenance programme, and the IEC 60706-5 [51] for enabling improved equipment maintainability through better testability features.

Another top-down approach which was introduced (particularly for aircraft maintenance) to provide significant improvements in availability and operational safety (whilst optimizing the costs of ownership), and has gone through a number revisions, is called Maintenance Steering Group-3 (MSG-3) [52]. This maintenance programme can effectively be tailored around reliability by any operator depending on historical data. Under MSG-3, maintenance tasks are broken down into zones, where all potential components are serviced/replaced in one shot, instead of having to go back multiple times to rectify the issue. The maintenance tasks and component replacements are no longer based on hard time limits, but rather based on reliability trending. This greatly reduces many repetitive tasks, and provides time and costs savings for airlines/operators. It should be noted that NFF events (also called 'hidden failures' within MSG-3) are analyzed as parts of multiple failures, and such failures on their own do no have any consequence. Here, the goal of preventive maintenance is to guarantee the availability of the system components that are essential to avoid the effects of multiple failures on safety, operation or economy. The question to speculate here is whether there are any NFF failures that can affect some components which directly impact the system operation (or production).

Recently, a set of procedures were introduced in the ARINC 672 Report [45], are directly aimed to provide the basis for a structured process for addressing the NFF problem in the aviation industry. As illustrated in Fig. 3, it provides criterions for decision taking regarding root causes, and describes the importance of taking maintenance actions at an early stage of the component repair cycle. It further highlights the necessary means of reducing costs by avoiding unwanted removing units from the aircraft. It should be noted that the guidelines are provided to be customized for specific operations environments.

It appears that there is a requirement in the design and production stages, to develop a more fault-tolerant system with re-

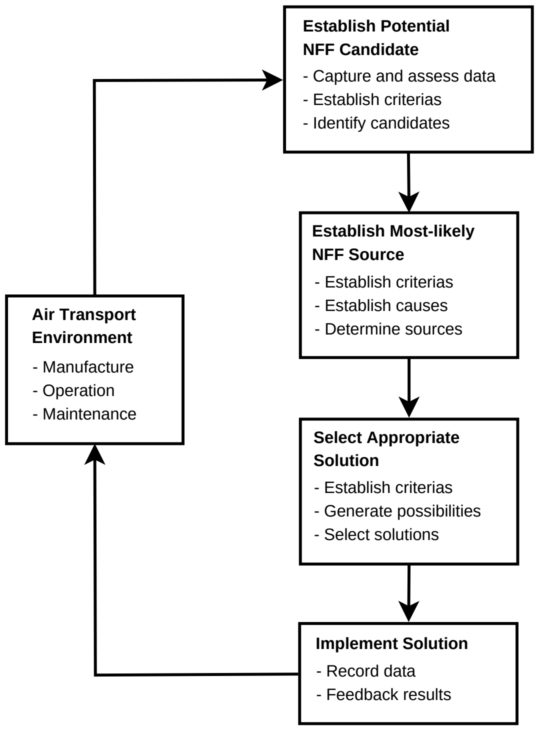

Figure 3: The ARINC 672 NFF Reduction process provides an interactive framework for various domains when customizing interdisciplinary processes.

duce NFF rates. An essential part will be to establish cross-discipline features and design solutions that can be applied to any engineering design. This will involved multi-disciplinary modelling of the root causes of NFF achieved by understanding and modeling electronic, mechanical and software interactions. Such an approach can lead to the development of design guides (or a handbook) covering the processes to be followed for the avoidance of the root causes of NFF at the design stage. Of course, these need to cover accurate fault models, fault trees, system understanding (to aid in recognizing false BIT alarm caused by e.g. sensors), system synchronisation problems (allowing root causes of BIT deficiencies). In order to compliment any design guidance and rule sets, solutions are required in order to link service experience with design knowledge to generate an official guidance standard to reduce NFF occurrences throughout a system life-cycle. These must be evaluated through a series of practical case evaluations within collaborating companies and through expert judgement.

There seems to be a lack of comprehensive international standards that deal with the NFF issue; which is also clouded by inconsistent terminology. It would therefore be useful to work towards harmonizing a set of generic maintenance-related standards that utilize a common terminology and framework; and the ARINC is a positive development moving towards the right direction.

6. Organizational Procedures and Administration

It is commonly accepted that the NFF phenomena arises from a minimum of two test levels [1]. At any test level, a fault may be recognisee and localized as belonging to an individual piece of equipment which, when re-tested, at a subsequent level, the recognition/localisation of the reported fault may be unsuccessful. This therefore means that a NFF event has occurred which arises from a number of reasons. It may be that the test at the preceding level was correct, but the attempts to subsequently replicate it at a subsequent level have failed. Perhaps this is due to the inability to re-create the conditions under which the preceding test was carried out, discrepancies in test procedure or human error. The second main reason could be that the error at the preceding level was incorrectly recognisee [53].

There is clear distinction between Cannot Duplicate (CND) and Retest OK (RTOK). CND occurs at the same level of maintenance where the fault was reported and RTOK occurs at subsequent levels of maintenance [41]. This leads to the conclusions that RTOK is a 'true' term which can be used for NFF. Even though it is in much of the literature CND however should not be technically described as NFF will only occur at 2^{nd} line maintenance. This maintenance process is illustrated in Fig. 4.

Jones and Hayes (2001) [13] argue that there are predominately three identifiable levels of where NFF events can occur:

1. Equipment Level: The operators find that the equipment does not function correctly and as a result a maintenance action is scheduled. The engineer however finds no problems during maintenance testing. This is carried out at 2nd line maintenance.
2. Board Level: The operators find that the equipment does not function correctly and during maintenance testing the engineer finds that a problem does exist and identifies a board to be removed and returned for repair. When subsequently tested, however the board functions correctly. This usually represents 3^{rd} line maintenance.
3. Component level: The board that has been removed is subsequently tested and a faulty component is identified. This component is replaced and the removed component is found on subsequent failure analysis to be functioning correctly. After the component has been replaced the board operates normally. This maintenance activity is usually carried out by the original equipment manufacturer.

It is still necessary not to neglect the fact that at some stage an event has occurred, be this a false alarm or component degradation, which has resulted in maintenance actions as described above (ending with a NFF decision). This event is known as the root cause of NFF and from literature studies can be attributed to several distinct types. Some typical root causes include [1, 40, 45, 54]:

1. Discrepancies and faults in test procedures: Such errors in process and procedures might exist but they are not known and lie unidentified but nevertheless generate NFF.
2. Incorrect fault reporting: Communication and having a common understanding and interpretation of the fault is

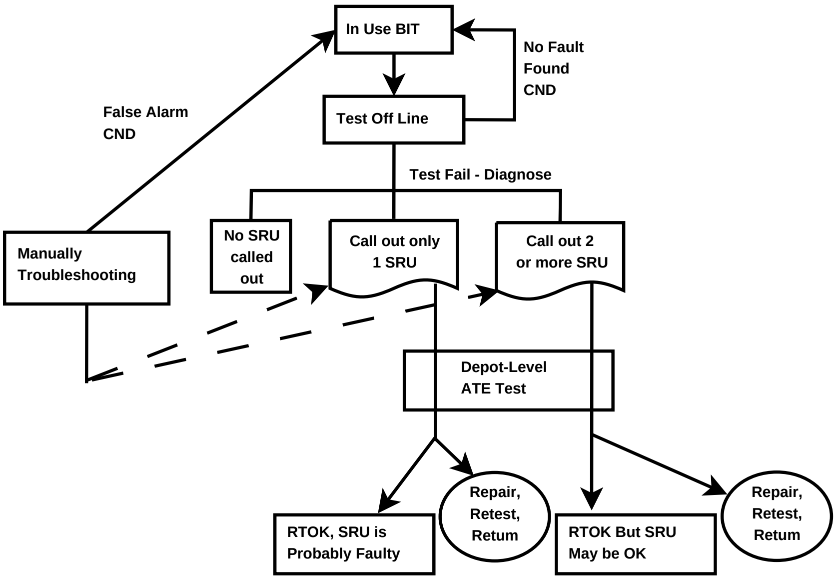

Figure 4: Test and Diagnostic Processes in Electronics.

sometimes just not achievable. People's perceptions and interpretation often mean the fault will not be properly diagnosed and found. There are also clearly human factors that are involved here.

3. Wrong processes applied: This may be deliberate through misinterpretation and presumed symptoms but also could be just lack of proper training.
4. Incomplete documentation: This cause might be processes that were not comprehensive when first devised.

6.1. Human Factors and Culture

Cultural factors clearly have similarities with human factors but tend to describe the corrective aspect rather than the individual. Often an organization can be overly bureaucratic and cumbersome in its response to change and may not even recognisee that it has a problem. However, it is becoming more widely acknowledged that one of the most significant contributory factors of NFF events are attributed to the behavior, skill sets and communication between an organization's technicians, engineers and management personnel [5]. The problem here lies more at the human level as there are so many human failings related to the variety of ways that faults are reported, the ways maintenance manuals that are written and presented, and the ways troubleshooting tests are designed. Adding the mix of training, expertise and experience that each engineer has in troubleshooting will affect how a company approaches NFF events. However, there are often insufficient resources to repair items on time, as well as not enough information, training and tools [55]. Hughes and Kornowa-Weichel (2004) [56] advocate that modern tools and equipment must be designed with the potential capabilities and limitations of the maintainers in mind. This also applies to fault detection in a maintenance environment where human factors should be taken into account to improve safety, reliability, efficiency and quality of job performance [57].

In any case, reasons that have been recognisee are often similar to those recognisee at the individual level that affects an individual's behavior:

1. Lack of communication [58]: At the personal level, perhaps between maintenance personnel when changing shift, poor communication may cause the new shift to misdiagnose the problem. Similarly lack of communication between experts in the organization means that vital information is not passed on to those who might then solve a regularly reported fault but on different equipment.
2. Not following the correct process [34]: Technicians can be known to take short cuts because they *'know best'* or they may make repeated assumptions which are incorrect. Operational pressures often cap the time available to line maintenance personnel for troubleshoot and are probably the major drivers for such behavior.
3. Workforce behavior [59]: Within the workforce behavior there is a reliance on norms that is prevalent: *'we have always done it this way and it always works'*. People are reluctant to admit their behavior, procedures and culture might be part of the problem. But whilst it will always get the equipment back on line, it may have involved changing three units where only one is truly at fault but now they have generated two NFFs in the system with all the attendant costs in the maintenance and supply chain.

Within industry, given the variety of NFF sources, each key player (such as the manufacturer's maintenance suppliers and operators) all approach NFF differently. This arises due to the nature of their self-interests and differing viewpoints, for example, do they take a company or a strategic view. Each of these key players therefore tends not to be transparent in the approaches which they adopt and the transference of knowledge and expertise in dealing with NFF is not part of the culture. Organizational culture may dictate that, taking a machine offline, or grounding an aircraft for a period of time, should take place at an appropriate time and for a period no longer than absolute necessary. As a result, the situation arises where internal pressure is placed upon the maintenance personnel to reduce their maintenance turnaround times [34]. This leads to a culture where units are replaced rather than the ‘root cause’ of a failure being identified and fixed.

The following are a key selection of issues within the organizational and workforce culture category:

1. Time pressures on maintenance operations [1]: There is an overriding need to get equipment back into service quickly. Availability of the equipment for service provides an overwhelming pressure on diagnosis and maintenance actions. This means that often On Speculative (On-Spec) replacements or maintenance actions is the quickest solution that may involve removing several LRUs, an activity that causes NFF further down the supply chain but has solved the fault at the original equipment. All too often, the pressure to return the equipment to service means that changing the three LRUs will be quicker than doing any detailed diagnostics to determine which of the three actually requires repair. The result, though, is that now there is one LRU that has the fault, and another two that will show up as NFF when subject to tests at the next level in the repair chain.
2. Organizational cultures: In many organizations, there is no cross-functionality, employee empowerment and encouragement to identify the root causes of reported faults. In other words wrong behaviors have been allowed to grow and take root. According to Murphy and Pate-Cornell (1996) [57], failures of complex engineered systems are often the result of management or organizational factors that influence the decisions of individuals. Thus, there could be organizational pressures affecting the work of technicians on complex systems leading to failures. An depicted in Fig. 5, an organization may influence the state of the individual (e.g. via selection, screening, training and workload), or it may affect their situation (e.g. information, procedure, organizational structure and culture); either of which can affect an individual’s action and thus have an overall effect on system risk.
3. Inadequate training or lack of training tools [60]: It is argued that NFF failure can escalate to become a safety issue, if the operator has not maintained a comprehensive training discipline for crews and line maintenance personnel. Therefore, training needs to competent if complicated diagnostics is to be achieved. Morris and Rouse (1985) [61] identified four training approaches to teach troubleshooting strategies to operators in order to identify and fix system faults:
   i Instruction of the theory; explaining the system functioning
   ii Troubleshooting practice exercises
   iii Guidance in the use of system knowledge, i.e. where to find the information, which manuals to use and how
   iv Guidance in the use of algorithms or rules

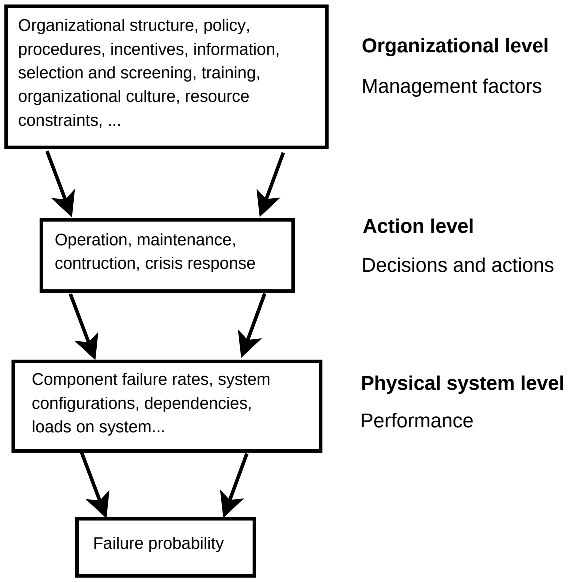

Figure 5: Generalized influence diagram of human and management effects on system risk.

   For troubleshooting, it can be asked whether it is better for a maintainer to learn to deal with problems according to procedures or by getting more knowledge about how the systems work. For familiar faults, the two types of approach worked equally well. But for novel faults, as the system-trained technicians have a superior mental model of the system, they used a better problem solving strategy which gave better results [4]. In addition, as a result of more and more automation being implemented into systems, traditional training approaches become less effective [62]. Thus it is better for the maintainers to form a mental model of the overall functional structure of the system to understand its contingencies and interactions, rather than accumulating compartmentalized knowledge.
4. Sharing information: There needs to be a culture and commitment to share knowledge between designers, manufacturers, service providers and operators. This may be easier said than done but it needs a system in place to share appropriate information between all the stakeholders to enable an effective, speedy transfer of shared knowledge. Soderholm (2007) [1] points out that there may be a number of possible weaknesses in using manuals as a means for sharing information, including poor sequence activities, a lack of accuracy or completeness, and a lack of user-friendliness. Another issue that renders the technician’s trouble-shooting task even more difficult is that there can be ineffective and often ambiguous test requirements resulting from a lack of distinction between physical faults and the functional anomalies by which they are detected and isolated.
5. Other major issues include:
   i Reluctance to change: Solutions that are likely to be disruptive to normal working practices are seen as unnecessary and a challenge to technical skills. Often an

organization will not change because in their view the organization is not the problem.

ii Inadequate historical data: It is essential that fault history on the equipment is known. Often the technician does not have the particular equipment's history to look at so the fact that the same fault is reoccurring is not obvious.

iii Ineffective Communication: This often manifests itself as lack of fleet or manufacturer advice. It may be that a particular fault is being seen across the fleet or a procedure is being improved by the manufacturer and this information, or rather solution would be relevant and stop some NFF but it is not being communicated.

7. Financial Implications

Williams et. al (1998) [10] claim that NFF failures can make up more than 85% of all observed field failures within avionics components. They also account for more than 90% of all maintenance costs, which can be can be attributed to:

1. A limited understanding of root cause failure characteristics of a complex system
2. inappropriate means of diagnosing the condition of the system
3. The inability to duplicate the field conditions in the laboratory

NFF events pose problems to almost everyone who is involved with the operational service - from customers to manufacturers, and their suppliers. There is however other major impacts upon business costs that are not so easily quantifiable such as the supply chain, maintenance performance, capacity, as well as indirect effects such as customer perception [63]. Janamanchi and Jin (2010) [64] recently proposed a financial model to analyze the trade-off between the financial benefits of reliability improvement and the costs associated with the implementation of Highly Accelerated Stress Screening (HASS)[5] in the context of manufacturing the automatic test equipment. The direct economic issues from NFF events are caused by putting units through the maintenance chain (replacement, logging, packaging, shipping, teasing and documenting) for no apparent reason. The impact of NFF could range from a mere nuisances, to increased financial costs, through to risking safety. Without high levels of confidence that a reported fault is not fixed correctly the first time, along with a high probability of re-occurrence, there will be a measurable impact on the business output.

Direct maintenance costs of any system can make a significant contribution to its overall cost of ownership. Wu et. al (2004) [22] identified that design and fault diagnosis are the key factors that influence such costs, whilst discussing a maintenance free operating period, and a fault diagnosis expert system for improvements. However, a large proportion of cost spent on NFF events can be attributed to warranty claims [26, 31, 55]. Depending on how the maintenance contract is setup, claims can be made to include human factors [65, 56] or intermittent failures [1, 60] (which constitutes quite a large proportion of the entire claim population). Prakash et al. (2009) [38] presented a methodology to determine optimal process adjustments in order to eliminate warranty related NFF product failures. Also, another method to minimize product warranty costs will be by embedding reliability in the early development phase of the system i.e. by designing out potential failure modes due to hardware, software, process and customer usage issues [66]. Either way, there will be a need for adequate data and evidence on the cost of NFF in order to make management recognisee the need to make the change. The costs, however, may not be so easy to establish and there is evidence to suggest that under many circumstances there is not even a willingness to establish what the NFF related costs are. As far as procedures and rules are concerned, defence organizations will necessarily cite the situation that military aircraft are built to safe-life criteria where there is no redundancy, unlike commercial aircraft built to fail-safe standards; this the RAF would maintain preclude them from adopting many of the new practices adopted by commercial operators such as the Subject To Aircraft Check (STAC) approach[6]. However, consider an organization such as the UK military. There used to be no real incentive to solve that part of the problem because their own maintenance and supply organizations would cope with the extra repairs required and indeed justified their existence. The organization is also too big and cumbersome to make the necessary changes easily. There were plenty of people but there was little focus on rising costs of such wasteful efforts.

7.1. In Aviation Systems

The problem is certainly not confined to any one sector, and various successes have been achieved in different industries at reducing costs. However the investment cost for NFF resolution is probably higher in the aircraft industry as equipment is more expensive, and downtime causes a large loss in revenue. Wasteful maintenance, whether it is at the aircraft, or further removed in the service support area, will cost a great deal of money for valuable resources, e.g. transportation costs of moving removed units to the appropriate workshop or manufacturer, which also includes the additional time spent on further testing and diagnostics. Other logistical activities also include the costs of processing activities and storage of the removed LRU's. A fault that re-occurs often doubles the costs [1], not to mention producing great frustration for managers, engineers and the op-

[5] Highly Accelerated Stress Screening (HASS) is a reliability screening process that is widely used to eliminate infant mortality, and hence improve the product mean time between failures.

[6] Subject To Aircraft Check (STAC) is an procedure introduced in civil aviation, which aims to reduce the likelihood of NFF occurring in the second line bays, while allowing licensed engineers to replace a component with a known serviceable item. If the aircraft suffers the same fault during its next flight (or very soon after), it is possible the originally removed item was in fact 'serviceable'. That item will therefore be returned to stock as 'STAC serviceable'. If, however, the aircraft does not display the same fault, the item follows the normal route to second/third/fourth line.

erators who rely on a reliable, working and cost-effective product. It is hence widely acknowledged that reducing NFF events have the potential to reduce overall maintenance costs in every industry in which they occur. These costs can be realized in terms of optimization of spare parts, increased logistic efficiencies, reductions in workshop time improved test equipment and personnel training.

Another factor is if numerous products exhibit NFF problems (or a single product has a regular occurrence of NFF), the manufacturer (or supplier) may receive an unfavorable reputation for unreliability and product replacements. These can be very costly to the manufacturer if the product is warranted and returns are much larger than forecast. Data released almost two decades ago by British Airways (BA) demonstrates that the airline industry has for some time recognisee that large sums of money can be wasted through high levels of NFF. In 1992 an audit of component removals highlighted an average of 8,000 items removed from British Airways fleet per month. A total of 14 per cent of components, across all workshops, were found to have NFF. Certain avionics equipment experienced 30 per cent NFF. Financially, taking into account direct and indirect costs, this equated to an annual NFF expenditure totalling £20 million [7]. In 1993, BA was extremely concerned at the high cost of removals where: nothing was found wrong, or the same fault reoccurred. As a result, a task force which established that it was not as bad as first suspected i.e. that 33% of all unscheduled removals were NFF. The data they captured for 1992 showed that 13.8% of all unscheduled removals that could be positively identified as NFF. Nevertheless this was costing BA £17.6M per year. The team also found that avionics components made up 80.4% of all registered NFF; these components represented 26.6% of all avionics removals. Figures published by the Air Transport Association (ATA) in 1997 estimated annual NFF costs for an airline operating 200 aircraft at $20M, or $100,000 per aircraft per year. It is likely that a similar figure is true for today's airline industry, but some commentators argue that taking into account a decade of inflation and economies of scale that the modern day figure could be at least twice the figure offered by the Air Transport Association. Other studies show that some 4500 NFF events were costing ATA member airlines $100M annually [58]. Recent efforts within the US Air Force to mitigate NFF focused on tackling individual avionic boxes, such as the Modular lower Power Radio Frequency (MLPFR), unit for the F-16. It was found that in excess of $2M in maintenance costs were being incurred annually for just that one unit at the maintenance depots [1].

Boeing's 787 Dreamliner has recently raised concerns after overheating batteries caught fire while the aircraft was parked at Boston's Logan International Airport [67]. Initial investigations had suspected the two lithium-ion batteries, but where ruled out as voltages had not exceeded the battery limits. Attentions later focused on the electrical system that monitored the battery voltage, charging and temperature. There was a direct knock-on effect on businesses as many airlines had to ground their aircrafts due to safety concerns. Analysts forecasted that while aircrafts are out of service, it costed Boeing an estimated £393M, while impacting their production line and future deliveries. This issue probably cost additional hundreds of millions as airlines are likely to seek financial compensation for their delays. Recently, the Dreamliner has been returned to service after some changes being made[7] to its battery systems, while the root causes of the battery failure still remain unknown to the authors of this paper.

The impact of NFF on maintenance costs are not confined to civilian airline operators, as in 1998, 10% of all Royal Air Force (RAF) aircraft had reported faults as NFF. These figures will obviously be different from operator to operator, as those who have their own shops (or at least service and test facility) would not be as worried as those who have a component exchange program. Also, Naval Air Systems Command (Navair) has been reported to be have spent $94M on NFF equipment removals due to wiring issues with unconfirmed faults [12][8]. In fact, findings demonstrated by Shannon et al. (2005) [68] show that for some Naval avionic systems NFF rates can grow up to 60%. This contributes to the overall spending on time, cost, manpower and resource allocation during maintenance activities.

7.2. In Consumer Electronics

Often an overlooked industry, which is also plagued by NFF occurrences, is that of consumer electronics [32, 34]. Specifically, the mobile phone industry had reported alarming figures outlining the cost of NFF. WDS Global reports that 14.3% of mobile handsets are returned as faulty within the first year of purchase by the consumer. In the UK this represents approximately £2.6M handsets (and £116M globally). Analysis has also revealed that approximately 63% of these returns have been made with no detectable faults. The mobile industry puts the combined costs of administration, shipping and refurbishment, collectively met by the operator, manufacturer and retailer at £35 per device. Over the course of a year this figure equates to potential UK mobile industry losses of £54M. More significantly, the cost to the global industry is estimated at £2.8 ($4.5) billion. Fig. 6 illustrates that the NFF occurrence in consumer electronics, such as mobile phones, is increasing each year. This may be due to increasing sophistication of the electronic components, including increases in complexity of user interfaces, functionality and inadequate operating guidelines/instruction product manuals.

7.3. In Transport Vehicles

Rail: Rail transport often employs a number of standards to guide implementation of control on safety risk in its system

[7]Investigators were still not able to identify precisely what caused the batteries to overheat, and, in one case, ignite. Boeing's fixes included better insulation for battery cells, a stainless steel box designed to encase the batteries and contain fire and vent possible smoke or hazardous gases out of the plane. Initial tests performed demonstrated that the batteries are now much less likely to overheat.

[8]The US Navy recognize NFF occurrences as a code: A-799. This is a situation where a reported fault at the organizational level cannot be reproduced (or detected) at another level of maintenance. The 'A' signifies the action taken indicating a 'discrepancy checked, no repair required', where as the '799' is a fault code indicating a 'malfunction could not be duplicated'

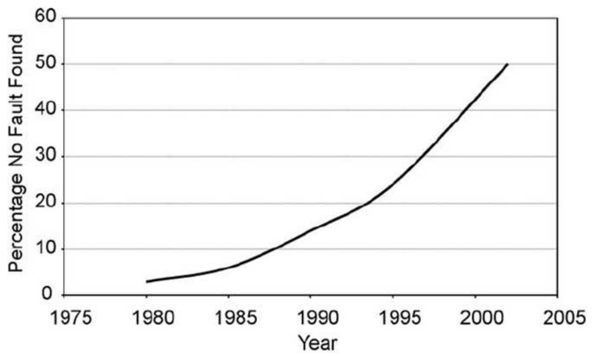

Figure 6: Percentage of NFF in Modern-High Volume Consumer Electronics.

development life-cycle (these include IEC 62278 [69] or EN 50126 [70]). These are often used to provide railway authorities with a procedure to enable the implementation of a consistent approach to the management of Reliability, Availability, Maintainability and Safety (RAMS) aspects to meet projects requirements. Since NFF occurrences can affect rail service operation, it is necessary to detect degradation before any heavy penalties could be incurred. Typically, scheduled maintenance and condition based monitoring are part of the maintenance policy, however, if the occurrences of failures are intermittent in nature, it becomes difficult to schedule maintenance in order to increase system availability and reduce cost.

There are no numbers quantifying the monetary effect of NFF on the rail industry in the currently available literature, but it is possible to highlight the potential cost of NFF in signalling failures by considering Railtrack. In 1999-2000, they reported a total of 25,000 signalling failures on the UK rail network resulted in delays totalling 760,000 minutes. A high proportion of signalling failures are attributed to mechanical failures in railway point systems, which results in a block to the rail signalling system, to prevent rail vehicles passing over potentially faulty points [24]. NFF incidents on railway points, often labeled as 'Tested-OK' are reportedly responsible for 11.3% of point machine faults. Therefore, it is easy to speculate that a substantial amount of the economic consequences of signalling induced delays, in terms of financial penalties, traffic throughput and customer dissatisfaction are attributed to NFF events [71]. As a percentage of total failure of common railway signalling assets rail industry records illustrate that the occurrence of NFF events is likely to be as high as 50% [72]. It is expected that similar wasted efforts and financial burdens will also be occurring in the Army, Navy, Wind Turbines, nuclear power plants and high-end car industries.

Automotive: Thomas et al. (2002) [24] highlighted the costs suffered by vehicle manufacturers in a case study for a Ford electronic ignition unit, where the inability to rectify the unit's continuous NFF issues led to legal action against the company resulting in a mandatory recall of the vehicles fitted with the electronic ignition. Information regarding financial costs of NFF within many industries in particular the aerospace industry, is difficult to obtain with very little information in the public domain. Some reasons for this which has become evident:

1. Sensitivity of the information: organizations are reluctant to risk commercial data falling into the hands of a competitor and within the aerospace industry there has always been a culture of secrecy surrounding maintenance activities.
2. Industries just do not know exactly how much NFF is costing: one aspect of this is that the complexity of the NFF issue results in difficulties in assigning an accurate financial figure within reasonable uncertainty levels.
3. In the current economic climate, many business departments are afraid to 'admit their shortcomings' and justifying the budget being spent on unknown faults.

This means that there is no complete, robust and reliable cost model currently available for measuring and calculating the financial impact of NFF. Although. the warranty costs within the automotive industry has been realized as the most significant overhead. Globally, the automotive sector spend 1% to 3% of its product revenue on warranty; warranty expenses associated with recalls are approximately $12.3 billion annually exceeding the manufacturers' yearly profits [60]. This adds up to a vehicle's life-cycle cost, and more importantly, indicates the proven potential of failure with a part which may reduce customer satisfaction to damage vehicles' brand image [13].

8. Safety Considerations in NFF

It can be argued that unless a NFF failure (that can have numerous potential causes) is a repetitive fault, which is influencing the system performance, then an isolated incident cannot be considered as a safety issue. However, the root cause of the NFF problem might well be a safety concern. Soderholm (2007) [1] classified NFF events into two distinct categories those that affect safety, and those that do not. An NFF occurrence which would have an impact upon safety would be the case where at any level of test there is a failure to recognisee and correctly localize an actual fault. Conversely, tests which result in false alarms, that is recognizing faults which do not exist will cause an inconvenience, but generally will not affect safety. In the case of inadequate diagnostic tools, the cause of a failure may be indeterminate - making repair impossible. This leads to fully functioning units being replaced, as a result of poor maintenance practice and inadequate testing methods faulty units often pass subsequent tests and are returned to the field as potential safety hazards. After a study into NFF occurrences related to a faulty ignition device on vehicles manufactured by the Ford Motor Company, Thomas et al. (2002) [24] concluded that more responsibility is required by manufacturers for ascertaining root causes, be that design/manufacturing flaws, inadequate testing or even operator/customer error, of returned safety-related products which have failed. Manufacturers should stop assuming that a safety-related returned product is fit for service if it has passed the required routine checklist tests; instead they should assume all safety-related products which are returned are treated as field-failures. The most crucial NFF failure type which is most significant when considering safety is that of intermittency. A high profile organization which has suffered from safety-related intermittent problems is NASA. In 2005, for not the first time, a space shuttle launch was delayed by three weeks due to an intermittent fault in a fuel-level sensor that appeared during tanking tests and was returned to an operational status without NASA ever discovering the root problem and hence fixing it. The intermittent cause of the circuitry that failed is one of four that would cut off the shuttle's three main engines if at least two showed that hydrogen fuel was running low. Should environmental launch conditions cause intermittent conditions to reappear inadvertently, the shuttle's safety would have been compromised. A multitude of back-to-back incidents within systems operated by NASA has indicated that increased intermittency is a significant issue in ageing electronics and their inability to detect this intermittence and certify its testing practices as being adequate to ensure safe and reliable launch operations was a major concern.

The danger of not dealing adequately with NFF events relating to intermittent faults is also demonstrated through an incident on-board a BMI A321 at 36,000ft whilst carrying 43 passengers on route between Khartoum to Beirut. An intermittent failure in the electrical power-generator systems presented numerous symptoms which included an uncontrollable rudder trim causing the left wing to dip by 10° and the aircraft to deviate from its intended course by 37km. In addition to this, both the pilot and co-pilot's instruments were affected with the primary and navigational flight displays amongst other instruments flickering or going entirely blank [73]. In this case the aircraft landed safely, but it does highlight from a safety perspective the need for intermittent faults to be successfully detected and localized during maintenance testing.

9. Conclusions

Organizations that often succeed in the long run have always fine-tuned their processes, procedures, and constantly evolved their ways to build a community both within and outside the business. In order to start a cultural change, there appears to be a definite need for ontology and, in some cases, an overhaul of the terminology used for NFF. Industrial engineers representing the UK aerospace industry have expressed their belief that the term NFF (which is the most frequent term in use) quite possible provides a hindrance to reducing those cases labeled as NFF. If the result of a test is described as 'No Fault Found' what does this really mean and how is it perceived in the mind-set of the test engineer? One way or another, there will be a repeat NFF event either because a faulty unit re-enters service or the wrong unit has been replaced. It needs to be acknowledged that the NFF phenomenon cannot be a single event rather a sequence that results in a series of actions at various maintenance levels until finally a decision is made to add the NFF label and perform one of the two actions above. What is the relationship between the system design and an NFF failure? Many authors and practitioners have alluded to the fact that there must be a relationship or connection between NFF levels and the type of equipment, complexity and equipment usage. The literature however has not uncovered any serious research into this and no published relationships have been found. It is however proposed that NFF taxonomy needs to be standardized and a mechanism for practising process stapling, in order to track NFF occurrences that have led to failure. Such areas which are of significant importance when trying to understand NFF would include:

1. The effect NFF failure has on specific types of equipment (both financial and on performance)
2. Identifying the conditions in which failures are frequent
3. The rate at which NFF failures reoccur
4. The main influencing root causes

It is also important to understand the dependency that NFF events have on repairable items, and how this may change throughout their operational life-cycle. Such questions which can be investigated include:

1. Do NFF problems become more common after initial repair than after the original delivery?
2. Does the number of repairs have any influence?
3. Is there any impact of component modification?

In Part II, the authors will be examining the recent technical solutions and troubleshooting methods that have been utilized for achieving diagnostic success.

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